International Journal of Environment and Resource
IJER Volume 1, Issue 1, August 2012 PP. 1-15
ISSN(online)
ISSN(print)
www.ij-er.org

Hydrochemical Characterisation and Classification of Groundwaters in the Sana'A Basin, Yemen

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(Abstract) In the present study, physico-chemical parameters were applied to characterize and classify ground- and spring water samples collected from the Sana'a basin-Yemen. A total of 24 groundwater samples from deep wells and 13 spring water samples were collected from the Sana'a basin between September and October 2009. Major anions (Cl^-, HCO_3^-, NO_3^- SO_4^{2-} and Br^-) and major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were measured. Additionally, the heavy metals As, Pb, Cu, Ni, Co, Cd, Fe, Mn, Al and Zn were measured in the groundwater samples. The physical parameters, which include water temperature, electrical conductivity and pH-value, and determination of hydrogen-carbonate, were measured on site. The ground- and spring water samples collected from the Sana'a basin were classified in groups according to their major ions (anions and cations) content. The classical use of the groundwater in hydrology is to produce information concerning the water quality. The classification was based on several hydrochemical methods, such as Ca^{2+} and Mg^{2+} hardness, Sodium Absorption Ration (SAR), Magnesium hazard (MH), saturation indices (SI) and Piper diagram. To ensure the suitability of ground- and spring water in the Sana'a basin for drinking purposes, the hydrochemical parameters were compared with the guidelines recommended by the World Health Organisation (WHO) and the Yemen National Water Resources Authority (NWRA) standards. In order to check the suitability of ground- and spring water for irrigation purposes the samples were classified based on MH and calculated SAR. The data were plotted on the United State SALINITY LABORATORY (U.S.S.L) diagram.

Keywords: Hydrogeochemistry of the Sana'a Basin; Groundwater Classification in the Sana'a Basin; Yemen's.

1. Introduction

The Sana'a basin was subjected to accelerated anthropogenic, economic and social developments during the last two decades. As a result of a high rate of population growth (7% per annum) (WEC, 2006), uncontrolled immigration to this area and the expansion of agricultural and industrial activities, the demand for water has increased tremendously in the last 20 years. The increasing demands meet limited resources. To satisfy the increased need for water, new groundwater wells have been drilled at various locations in the basin, and the abstraction from all groundwater sources has increased beyond the perennial yield of the Sana'a basin which led to rapid drop of the groundwater level ranges between 4 and 5 m/year (WEC, 2002). This problem seems even more serious when taking into account the gradual degradation of the water quality and marked drought events recorded in the country within the last few years. The overexploitation of the groundwater in the basin bears the risk of wells falling dry, a degradation of the water quality due to infiltration of sewage water, particularly in the alluvium aquifer below the urban area and in the sandstone aquifer in the northern part of the basin, and increasing salinities due to intensive groundwater pumping. Furthermore the groundwater in the agricultural area could be contaminated by the increased and uncontrolled application of the fertilizers and pesticides.

In a rather recent evaluation study of water resources in the country, FOPPEN (2002) assumed that the Sana'a basin would not only enter a phase of water deficit in the near future. However, he also attested that, if no remedial and immediate solution actions were undertaken to correct the deficit, water shortage in the basin could become a critical problem.

In the present study the water samples were divided into different groups or classes according to their chemical

composition. For classification purpose, four categories were used; the total water hardness (TH), Sodium Absorption Ration (SAR), Saturation Index (SI) and Piper diagram. The classification associated with evaluation of the water quality in the Sana'a basin according to its use for the various proposes, e.g. the water hardness is an important parameter for the assessment of the water quality for domestic purposes. For further evaluation of the water quality for domestic purposes, the guideline values recommended by WHO and NWRA were used.

About 80% of water in Sana'a basin is used for irrigation purposes, so the evaluation of the water quality for this purpose is an important goal of this work. For this evaluation, the SAR and salinity hazard diagram used by United State Salinity Laboratory (USSL) is used.

2. General characteristics of the study area

2.1. Regional setting, topography, climate

The Sana’a basin is one of the most important highland groundwater basins in Yemen. The basin is located in the central Yemen highlands at an elevation of about 2200 meter above sea level (m.a.s.l.) between 15° 21' N and 44° 12' E covering an area of about 3.200 km^2. (WEC, 2002) (Fig. 1)

The climate in the Sana’a basin is semi-arid. The hottest season in Sana’a is from June to August, and the coldest season is between December and February, with maximum and minimum monthly temperatures in June 31°C and December 4°C, respectively. The average maximum annual temperature in Sana’a from 1983 to 2002 was recorded in June at 31°C. The minimum temperature is 24°C in December. The average minimum annual temperature is 4°C in December-January and maximum 15°C in July. The average monthly temperature ranges between 15 and 25°C. The average monthly humidity in Sana’a ranges between 35 % in June and 52 % in April (NWRA, 2003)

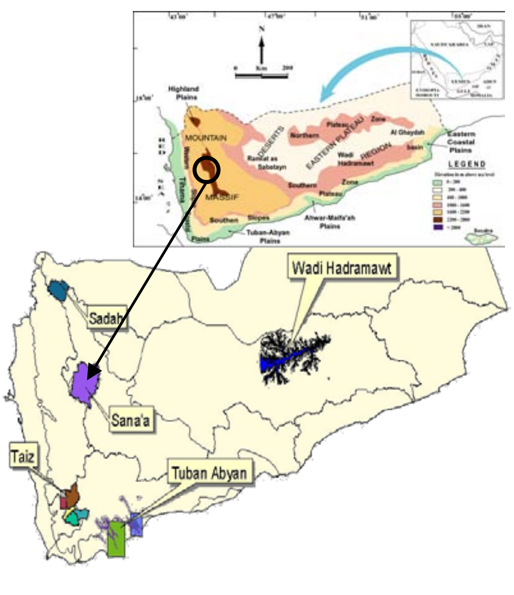

Figure 1: Location of the study area (after NWRA, 2003)

2.2. Hydrogeological conditions

2.2.1. Geology

The oldest sedimentary Formation in the region of Sana'a is the Amran Series (Middle to Upper Jurassic) which comprises of limestones, marls and shaly limestones some 350 to 1000 m thick. The Amran outcrops in the north of the basin, covering about 15% of the Basin area. It occurs at depth beneath the Sana'a plain. At the airport, the top of the Amran is approximately 350 m deep, at Ar Rawdah it is 500 m deep and further south near Sana'a it is 900 m deep or more. The Amran is overlain by a sequence of lagoonal shales, marls and fine grained sandstones interbedded with lignite probably of Upper Jurassic or Lower Cretaceous age which outcrop in a narrow band in the north-eastern part of the basin.

The Tawilah Sandstone (Cretaceous to Tertiary) comprises a series of continental cross bedded sandstones generally medium to coarse grained with interbedded mudstones, siltstones and occasional silty-sandstones.

The overlying Medj Zir Formation is a finer grained sandstone with a higher proportion of siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It has proved difficult to distinguish the Tawilah and Medj Zir both in aerial photographs and drill cuttings. They are therefore mapped as one formation and referred to as the Tawilah Sandstone or "Cretaceous Sandstone". The Cretaceous Sandstone outcrops over about 15% of the Basin area in the northern part of the Basin. It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by the overlying Tertiary volcanics. The Tertiary volcanics (formerly called the Trap Series) outcrop over some 35% of the area of the Sana’a Basin. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary deposits in the south of the Basin. The sequence is divided into two groups. The lowest group is the "Stratoid Volcanics" which include the Basal Basalt (a dense homogenous basalt flow with columnar jointing), basalts, tuffs and pyroclastics interbedded with fluvio-lacustrine deposits. The upper "Chaotic volcanics" comprise mixed basalt flows and rhyolite lavas. The total thickness is variable, reaching an estimated maximum of 700 to 900 m. Basic intrusive rocks of Tertiary age are present throughout the area in the form of volcanic plugs, dykes and sills. The alignment of the volcanic necks is oriented NNW-SSE. Dykes are well fractured and oriented NNW-SSE and NNE-SSW. Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the north west of the Basin interlayered with tuffs and alluvial sediments. The Quaternary Basalts have a total thickness of about 100 to 300 m and cover about 20% of the area of the Basin. They overlie the Amran Limestone, Cretaceous Sandstone and Tertiary Volcanics.

Unconsolidated deposits of the Quaternary cover approximately 15% of the Basin area. They are confined to wadi beds and low areas that form the Sana'a plain.

Deposition appears to have been of fluvio-lacustrine nature which led to the accumulation of clays and silts in basins 100 to 300 m deep. Coarse grained colluvium and alluvium occurs in the wadi beds at the foot of hills.

The sedimentary sequence is block faulted and gently folded. The regional dip is southwards under cover of the Tertiary Volcanics.

The unconsolidated Quaternary deposits provide a poorly permeable aquifer which has been heavily exploited in the Sana’a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine grained nature of the deposits in the plain, recharge is expected to be mainly indirect, into coarse grained material along wadis and at the base of the hills.

2.2.2. Hydrogeology

The Amran limestone is generally considered to be a poor aquifer although supplies can be obtained from zones of secondary permeability. Karst features however are poorly developed. The depth to water is over 100 m in the plateau area in the northwest of the basin. In the northeast in valleys leading to the Wadi al Kharid the depth to water is less than 35 m and groundwater is abstracted mainly by means of dug wells.

The Cretaceous sandstone forms the main aquifer in the region. It has low regional permeability but locally higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a where it either outcrops or occurs beneath an unconsolidated cover of up to 50 m thickness. Depths to water in the main area of abstraction were about 30 to 40 m in the early 1970's but have declined by 2 to 4 m/yr since. In the south of the basin the sandstone is confined beneath several hundreds of meters of Tertiary volcanics. The basalt flows and stratoid sequences of the Tertiary volcanics act as aquicludes, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high level springs. The upper layers of the volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the basin. Here they are exploited together with the unconsolidated aquifer by dug and drilled wells. The Quaternary basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the formation is saturated it provides an unconfined aquifer. Water levels are deep ranging from 60 to 130 m depending on the elevation. Wells are generally limited to the southern edge of the outcrop where water levels are less than 100 m deep. In the rest of the area, surface water is stored in cisterns to provide water for domestic purposes.

The unconsolidated Quaternary deposits provide a poorly permeable aquifer which has been heavily exploited in the Sana’a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine grained nature of the deposits in the plain, recharge is expected to be mainly indirect, into coarse grained material along wadis and at the base of the hills.

3. Methods

3.1. Sampling campaigns

Sampling campaign in the Sana’a basin, which includes groundwater and spring water samples, was carried out in September/October 2009 by the author accompanied by a representative of the cooperation partners Water and Environment Centre (WEC).

A total of 24 wells for groundwater sampling, and 13 springs were chosen. Two samples were taken from each site, one sample for analysis of major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and selected heavy metals (As, Pb, Cu, Ni, Co, Cd, Fe, Mn, Al, Zn), and one for major anions (Cl^-, SO_4^{2-}, NO_3^- , Br^-). The heavy metals were analysed in all of the 24 groundwater samples.

Polyethylene bottles (50 ml) with watertight caps were used for the sampling. The bottles were pre washed with the water sample and filled up entirely and stored in cool-box and later stored in a refrigerator by 4 °C until the transport to the Hydrogeology Laboratory at FUB for the analyses. The samples for determination of the major cation and heavy metals were acidified with two drops of ultra pure HNO_3 to prevent the oxidation.

Groundwater samples were collected mostly from deep boreholes (drill wells); only three samples were collected from dug wells. All the wells (drill and dug) are equipped with pumps. Total depth of the drill wells ranges between 56 m and 450 m. The dug wells are 60, 70 and 80 m depth.

3.2. Analysis

3.2.1. On-site Analysis

The physicochemical parameters such as temperature, pH, and electrical conductivity (EC) of the ground- and spring water samples were measured in the field with WTW Microprocessor Conductivity Meter LF 196 device provided by FUB. Because of the time consuming, the determination of hydrogencarbonate was carried out means a quick test in the laboratory of WEC in Sana’a within few hours after sampling.

3.2.2 .Laboratory analysis

The laboratory analysis comprises determination of major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}), anions (Cl^- , SO_4^{2-}, NO_3^- , Br^-) and selected heavy metals (As, Pb, Cu, Ni, Co, Fe, Mn, Al, Zn). Precision and analytical methods are detailed in table 1.

Major ions were analyzed in a total of 24 groundwater and 13 spring water samples. The heavy metals were measured only in the groundwater samples. The analyses were performed at the hydrogeology laboratory of FUB by labor assistant Mrs. E. Heyde. Measurement of K^+, Na^+ , Ca^{2+} , Mg^{2+}, Mn, Pb, Cu, Fe, Cd, Ni, Co, Zn, Al were conducted by inductively coupled plasma optical emission spectrometry (ICP-OES), Cl^- ,NO_3^- , SO_4^{2-} , Br^- by Ion-

chromatography (IC) and flame atomic absorption spectrometry (FIAS AAS) was used for As.

Table 1: Detection limit and analytical methods

Parameter	Method	Type	Detection limit
K^+	ICP	Optima 2100 PerkinElmer	0,2 mg/l
Na^+	ICP		0,2mg/l
Ca^{2+} ,Mg^{2+} , Mn, Pb, Cu, Fe, Cd, Ni, Co, Zn, Al	ICP		0.02 mg/l
As	FIAS AAS	PerkimElmer	0,005 mg/l
Br^-	IC	DX 500 DIONEX	0,5 mg/l
Cl^- ,NO_3^- ,SO_4^{2-}	IC	DX 500	0,5 mg/l

4. Results and discussion

All physicochemical parameters measured in the field and laboratories are presented in the table 1 and 2 in the appendix. The results are compared with the WHO and NWRA guidelines for drinking water quality and discussed in other section in this work.

4.1. Charge balance

The analytical results for the groundwater and spring water samples can be assessed for reliability by determining whether the equivalents of the major cations and anions are approximately equal (HEM, 1985). All water samples are electrically neutral, meaning that the sum of the positively charged cations must be exactly to the sum of the negatively charged anions (WEIGHT, 2008).

A charge balance error can be calculated by the following relationship (WEIGHT, 2008):

$$balance(\%) = \frac{\sum cations - \sum anions}{\left(\sum cations + \sum aninons\right)/2} * 100 \quad \textbf{(eq. 1)}$$

The hydrochemcial analysis is given in mg/l and was transformed to mmol/l to calculate the balance in % according to equation 1. Water analyses are normally considered acceptable if the charge balance error is within ±5% using the equation 1. The charge balance error for the analyses associated with this study varied from -5.84 to +4.91 % for groundwater samples and -5 to +0.10 % for spring water samples (tab. 1 in the appendix). Because of the minor error occurs in one sample (-5.84%), the sample was considered in the evolution.

4.2. Physicochemical parameters

Physicochemical parameters, which include water temperature, pH and the EC, were measured in ground- and spring water samples taken from the Sana'a basin.

4.2.1. Water Temperature

The temperature of the groundwater samples and spring water was measured on site during water pumping/sampling. Spring water temperatures were measured directly in the spring.

In general, the temperature of groundwater increases with depth because of the hydrothermal gradient in the area, which, in turn, is influenced by the volcanic activity among other tectonic factors. It is therefore expected that the deeper the well the higher its water temperature, especially if it lies within the vicinity of areas subjected to recent volcanic activity or along fault zones (WEC, 2004). Water temperature in the shallow dug wells located in the alluvium aquifer (samples: GW-2, GW-16 and GW-17) could be influenced by the radiation of the sun. About 33% of the total samples, mainly from dug and shallow wells, show low temperatures ranging between 20 to 25 °C while 37% shows temperatures ranging between 26-30 °C. Temperatures more than 31 °C were recorded in 29% of the total samples; most of them located in the northern part of the basin in the limestone aquifer. The temperature range between 31-36 °C is interpreted as reflecting geothermal effects throughout the whole area.

The springs generally have lower water temperatures ranging between 18 to 23 °C due to the contact with the cold atmosphere.

4.2.2. pH-values

The lowest pH value of the groundwater was observed in the sandstone aquifer in north-eastern part of the basin with pH value 5.6, and the highest values with 9.4 in the volcanic aquifer in southern part of the basin. It is observed that 54% of the water samples have pH-values in the range of 7.0 and 8.0. The volcanic and alluvium aquifers have the highest pH-values of the groundwater in the Sana'a basin with pH-values range from 7.5 to 9.4 (alkaline water).

The samples from sandstone and limestone aquifers have lower pH-values ranging from 5.6 to 7.6. The groundwater in these aquifers is mainly influenced by the hydrothermal activity (SAWAS, 1996)

Six of the groundwater samples show pH-values outside of the range recommended by WHO (6.5-8.5). The values are above the recommended value in the samples GW18, GW19 and GW20 in volcanic aquifer with pH 9.4, 8.9, 9.0 respectively; and below the recommended value in the samples GW-5, GW-6 in the limestone aquifer and in GW-7 in the sandstone aquifer in the northern part of the Sana'a city with 6.3, 6.3 and 5.6 respectively. The groundwater in this part is affected by the infiltration of domestic sewage via cesspits (SAWSA, 1996).

In the study area, 11 water samples from springs (85%) show pH values above 7, and only two samples recorded pH values below 7 (SW-3 and SW-8 with pH-values 6 and 6.7,

respectively. This deviation could be due to the long path flow in the underground, consequently the contact with the bearing rocks. Some of the springs were contaminated. The values in SW-3 and SW-10 exceeded the WHO value with values of 6 and 9.4, respectively.

4.2.3. TDS and electrical conductivity (EC)

The EC was measured in µS/cm in the field during water sampling at 24 groundwater points and 13 springs. TDS was calculated in mg/l using the equation:

TDS = 0.65 * EC (eq. 2)

The EC and TDS of the water is a function of temperature. The higher the temperature the higher the dissolved minerals, consequently higher EC; this is the reason why the groundwater has higher EC than the spring water.

The TDS of the groundwater in the Sana'a basin is affected mainly by the concentration of the major cations Mg and Ca and major anions HCO_3 and SO_4. The TDS of the spring water samples is affected by the cations Mg, Ca and Na and the anions HCO_3, SO_4 and Cl. The concentration of these ions shows systematic increases with TDS. The TDS increases with the increase of the contents of the water from these minerals.

The concentration of total dissolved solids in the groundwater samples and spring water ranges from 1319.5 to 182 mg/l and from 403 to 149.5 mg/l respectively. The low TDS values in the groundwater samples, particularly in the sandstone aquifer, indicate fresh recharge water.

The measured electrical conductivity values are found to be within the range of 2030-280 µS/cm at 25 °C in the groundwater samples, while the springs show lower values ranging between 620 and 230 µS/cm. The large variation in EC is mainly attributed to lithologic composition and anthropogenic activities prevailing in the region.

It is common that calcium bicarbonate and calcium sulfate water-type generally have the lowest EC-values (Davis, 1966). This was observed in the southern part of the basin in the volcanic aquifer where the lowest EC-values were found and ranging between 470 and 280 µS/cm. The dominant water-type in this aquifer is Ca-HCO3-SO4 and Ca-HCO3. As a result of the dissolution of the minerals calcite, dolomite and gypsum which are presented in Amran limestone, the highest EC-values were recorded in north-eastern part of the basin in the limestone aquifer with values ranging between 2030 and 560 µS/cm.

The measured EC-values result indicate that almost all the ground- and spring water samples are within the permissible limits of 1500 µS/cm recommended by WHO, with the exception of GW-6 in the limestone aquifer where EC was found to be 2030 µS/cm. However, this value is within the permissible limits of 2500 µS/cm recommended by NWRA.

The calculated TDS values for both groundwater and spring water samples are within the WHO and NWRA standards (1000 mg/l and 1500 mg/l, respectively). Only two of the groundwater samples, namely GW-5 and GW6 in the limestone aquifer, exceeded the calculated TDS values the permissible limits recommended by WHO with 1280.5 and 1319.5 mg/l, respectively.

4.3. Chemical composition

4.3.1. Major ions

Concentration of major cations and major were measured in a total of 37 ground- and spring water samples. The results of the labor analyses are given in tables 1 and 2 in the appendix and shown in figures 2 to 5.

Ca, Mg, SO_4, HCO_3, K and Na show the highest concentrations in the northern part of the basin in the limestone aquifer. The highest concentration of Mg and Ca was found in sample GW-6 and GW-5, whereas the lowest values were found in samples GW-20 and GW-18 in southern part in the volcanic aquifer, respectively. The concentration of Mg and Ca ranges from 0.18 to 75.5 mg/l and 2.9 to 326 mg/l. SO_4 and HCO_3 show the highest concentrations in sample GW-5 with 812 and 787.5 mg/l; the lowest value of SO_4 is 14 mg/l in sample GW-15 in the western part in the sandstone aquifer, and 126 mg/l for HCO_3 in sample GW-2 southern part in the alluvium aquifer. The high concentration of Mg, Ca and HCO_3 ions in groundwater can be explained by the solution of calcite, dolomite and gypsum which are all present in the Amran limestone group. SO_4 ion concentrations are probably derived from weathering of sulfate and gypsum-bearing sedimentary rocks of the Amran group.

Generally Na, unlike Mg and Ca, is not found as an essential constituent of many of the common rock-forming minerals. Na content of the groundwater in the study area ranges from 274 to 11.1 mg/l. The highest value was found in sample GW-8 in the northern part in limestone aquifer and the lowest in GW-15 in western in the sandstone aquifer. Potassium concentration of groundwater samples in the study area range between 0.4 mg/l in sample GW-20 southern part in the volcanic aquifer to 16.4 mg/l in the northern part in limestone aquifer. This reflects the natural ratio with sodium of less than one tenth the concentrations (DAVIS, 1966).

Nitrate was presents in all of the spring and groundwater samples. This might originate from human activity or from minor NH_4 gas emissions from volcanic activity into the groundwater system where it is oxidized to NO_3 (FOPPEN, 2002).

The highest nitrate and chloride concentrations were measured in samples GW-16 with 121 mg/l in the central part of the Sana'a city near the new campus of Sana'a University and in sample GW-4 with 252 mg/l, which comes from the eastern part of the basin in the alluvium aquifer. Groundwater in these parts of the basin is affected by the infiltration of domestic sewage via cesspits and the subsequent oxidation of NH_4 to NO_3 (SAWAS, 1996). This area is dominated by a high population density and lacks a sewer system.

Concentrations of Br were compared with EU- guidelines for drink water and were classified as high, exceeding the EU-standard (0.01 mg/l) in all of groundwater and spring

water samples. The highest value with 2.5 mg/l was found in sample GW-4 in the northern part and the lowest concentration recorded with 0.3 mg/l in samples GW-13, GW-14 and GW-15 in the sandstone aquifer in the west, and samples GW-23 and GW-24 in the volcanic aquifer in the south.

The spring water generally shows a low mineral content. TDS of the spring water samples ranges between 402 to 149.5 mg/l. The springs are located in high elevation ranges between 2103 to 3022 m.a.s.l; therefore the spring water is cold with temperature ranges between 23 to 18 °C. The low solubility associated with these temperatures, in combination with short flow paths and residence times affects the concentrations in this area.

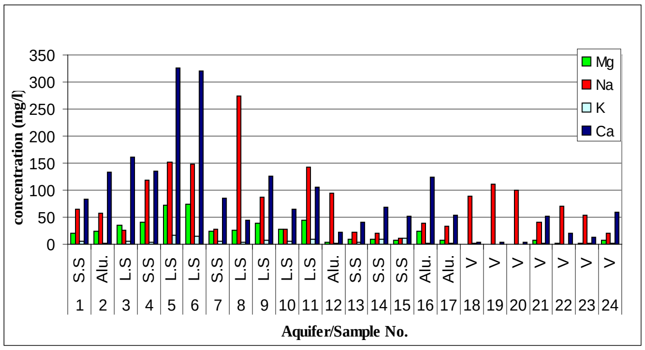

Figure 2: Major cations in the groundwater samples

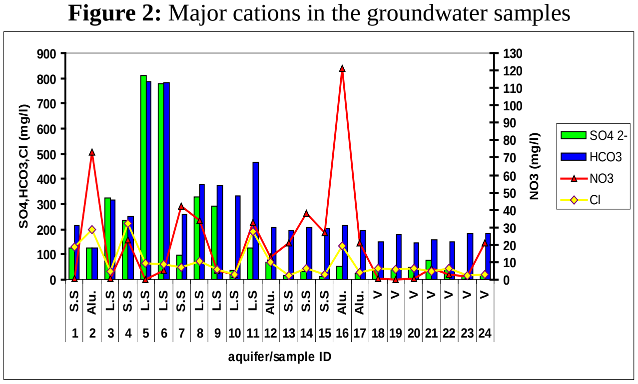

Figure 3: Major anions in the groundwater samples

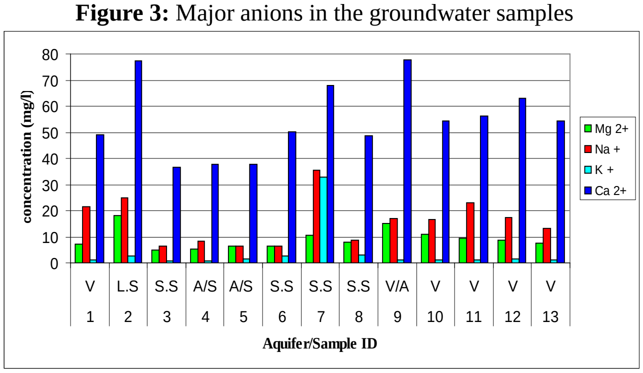

Figure 4: Major cations in the spring water samples

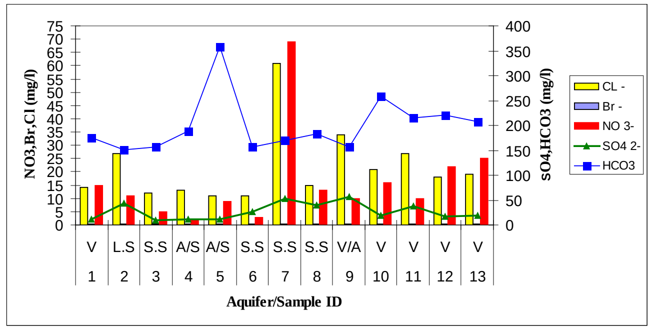

Figure 5: Major anions in the spring water samples

4.3.2. Heavy metals

Selected heavy metals As, Pb, Cu, Ni, Co, Cd, Fe, Mn, Al, Zn were analyzed in the groundwater samples taken from the Sana'a basin. No analyses were conducted in the spring water samples. The measured values are presented in Figure 6.

The measured values show that the concentration of the heavy metals Pb, Cu, Ni, Co, Cd in all 24 groundwater samples is below the detection limit. This is probably due to the absence of heavy industry in Sana'a region, since industrial activity is the main responsibility for the presence of the heavy metals in wastewater and later in the groundwater (Al-HAMDI, 2000). The heavy metals As, Mn, Al and Zn were found in low concentration in some of the samples. The measured values are not exceeded the values recommended by WHO, 2004 and by NWRA, 2000.

Iron is the most concentrated heavy metal. It was found in 21 out of 24 samples in high concentration; however, the measured values were not exceed the value recommended by NWRA, 2000 (1mg/l). The highest concentration was found in the limestone aquifer in the samples GW-5 with 1 mg/l, and the lowest measured values were found in the sample GW-7 and GW-9 with 0.03 in the sandstone and limestone aquifer, respectively.

The low concentration of the heavy metals As, Mn, Al, Zn and higher Fe in the groundwater in the study area seems natural, however, the relative high concentration of e.g. zinc and Al in some samples points towards to anthropogenic effects such as the application of fertilizers and pesticides in agriculture areas.

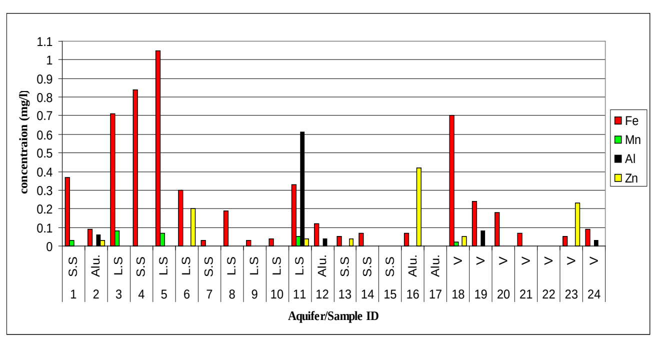

Figure 6: heavy metals in groundwater samples

4.4. Water classification

The classical use of water analyses in groundwater hydrogeology is to produce information concerning the water quality. The water quality may yield information about the environments through which the water has circulated. The main objective following the hydrogeochemical assessment is to determine groundwater suitability to different uses based on different chemical indices. In this study, assessment of the suitability for drinking and domestic consumption was evaluated by comparing the hydrochemical parameters of groundwater in the study area with the prescribed specification of World Health Organization (WHO, 2004) and NWRA, 2000. The calculated SAR was used to assessment the suitability for the irrigation purpose.

4.4.1. Classification based on total hardness (Ca^{+2} and Mg^{+2} hardness)

The calcium and magnesium hardness is the concentration of calcium and magnesium ions. The degree of hardness of drinking water has been classified in terms of its equivalent $CaCO_3$ concentration in four categories (WHO, 2004): soft water, hard water, medium hard water and very hard water (tab. 2). Very hard water is not desirable for many domestic uses; it will leave a scaly deposit on the inside of pipes, boilers, and tanks. Hard water is mainly an aesthetic concern because of the unpleasant taste that a high concentration of calcium and other ions give to water. It also reduces the ability of soap to produce lather, and causes scale formation in pipes and on plumbing fixtures. Soft water can cause pipe corrosion and may increase the solubility of heavy metals such as copper, zinc, lead and cadmium in water. In some agricultural areas where the fertilizers are applied to the land, excessive hardness may indicate the presence of other chemicals such as nitrate (WHO, 2004). Hardness in water is the most common water quality problem especially when the main water sources are deep wells as in the Sana'a basin.

Water hardness in most groundwater is naturally occurring from weathering of limestone, sedimentary rock and calcium bearing minerals. Waters that filtrate through limestone are prone to hard water. This is because of rainfall, which is naturally acidic containing carbon dioxide gas, continually dissolves the rock and carries the dissolved minerals into the groundwater system.

The guideline value for drinking water recommended by WHO for water hardness is 500 mg/l (WHO, 2004), this value was also recommended by NWRA, 2000. The optimum range of hardness in drinking water is from 80 to 100 mg/L (WHO, 2004).

The calculated total hardness of ground- and spring water samples in the Sana'a basin shown in figure 7 and 8 and presented in table 3 and 4 in the appendix, respectively. In comparison the results of this study with the classification values given in table 2, ground- and spring water in the Sana'a basin could be classified in four groups:

Group 1: very hard water

Most of the 37 measured water samples are very hard (49% of the total samples). Water of this group has hardness concentrations range between 181 and 1.110 mg/l. The highest values were found in the limestone groundwater aquifer in the northern part of the basin. The minerals calcite and magnesium are thought to derive naturally from rocks of the Amran limestone group which comprises dolomite and gypsum.

Group 2: hard water

About 30% of the total water samples represent this water type. This type is to be found mostly in the volcanic and sandstone aquifer in the southern and western part. Water samples have hardness concentrations range between 139 and 179 mg/l.

Group 3: medium hard water

Only four samples represent this water type. It is common in spring water in the alluvium aquifer which is located in contact with sandstone. Hardness concentrations in water sample this type range between 71 and 120 mg/l.

Group 4: soft water

About 14% of the water samples are soft water with a low hardness ranging between 8 and 58 mg/l. This water type was observed in volcanic groundwater aquifer in southern part. Water passing through igneous rocks is thought to dissolve only small quantities of minerals.

Table 2: Classification of drinking-water based on total hardness (WHO, 2004)

concentration as $CaCO_3$ (mg/l)	classification
0-60	soft water
60-120	medium hard water
120-180	hard water
> 180	very hard water

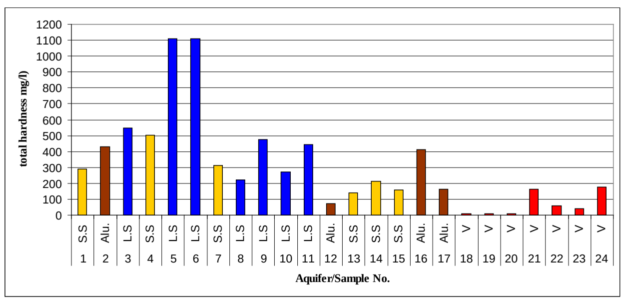

Figure 7: Total hardness in groundwater samples-Sana'a basin

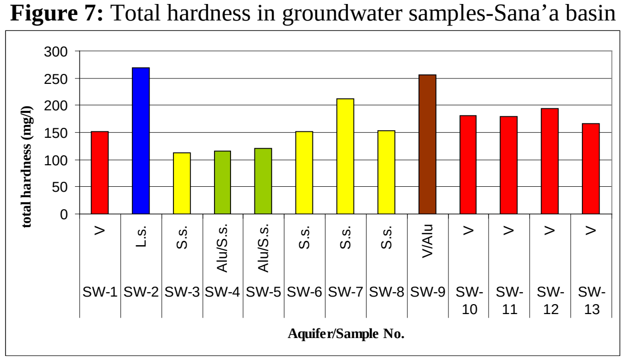

Figure 8: Total hardness in spring water samples from Sana'a basin

4.4.2. Classification based on salinity and sodium hazard (SAR)

About 80% of groundwater in the Sana'a basin is used for irrigation. The water quality evaluation in the study area is carried out to determine their suitability for agricultural purposes. The suitability of groundwater for irrigation is contingent on the effects on the mineral constituents of the water on both the plant and the soil. In fact, salts can be highly harmful. They can limit growth of plants physically, by restricting the taking up of water through modification of osmotic processes. Also salts may damage plant growth chemically by the effects of toxic substances upon metabolic processes. Salinity and toxicity generally need to be considered for evaluation of the suitable quality of the groundwater for irrigation (TODD, 1980). Parameters such as EC and sodium adsorption ratio (SAR) and the standard diagrams were used to assess the suitability of water for irrigation purposes. The method published by the US SALINITY LABORATORY, STAFF (1954) was used for the classification of our samples (Fig. 6). The calculated values were plotted in a Wilcox diagram using the software program AquaChem 4.0. The plot can be used to quickly determine the viability of water for irrigation purposes. The Wilcox plot is also known as the U.S. Department of Agriculture diagram. The SAR is plotted as Sodium Hazard on the Y-axis in the Wilcox plot; and the measured EC (Cond.) is plotted on the X-axis as Salinity Hazard. The Conductivity (EC) is by default plotted using a log scale. Tables 3 and 4 in the appendix show the calculated values.

4.4.2.1. Salinity Hazard

Excess salt increases the osmotic pressure of the soil solution that can result in a physiological drought condition. Even though the field appears to have plenty of moisture, the plants wilt because insufficient water is absorbed by the roots to replace that lost from transpiration. The total soluble salt content of irrigation water generally is measured either by determining its EC (as in this study) or by determining the actual salt content in parts per million (ppm). The conductivity values ranged from 280 to 2030 µS/cm. Irrigation water with an EC of < 700 µS/cm causes little or no threat to most crops while EC > 3000 µS/cm may limit their growth (TIJANI, 1996). Based on the US Salinity Laboratory classification (1954) the salinity hazard for water samples in the Sana'a basin is classified as medium to high (Fig. 6). All of the spring water samples and most of the groundwater samples belong to medium salinity hazard as per the salinity hazard classification in the basin. Fourteen groundwater samples fall in the medium salinity hazard category (C2) while a few of the samples belong to the high salinity hazard category (C3). None of ground- and spring water samples show low salinity contamination (C1). Groundwater that falls in the medium salinity hazard class (C2) can be used in most cases without any special practices for salinity control. However, water samples fall in the high salinity hazard class (C3) may detrimental effects on sensitive crops and adverse effects on many plants. Such areas require careful management practices. As it can be seen only small parts in north of studied area (in the limestone aquifer) have high salinity hazard while the samples from south, east and west of the studied area had medium salinity and are suitable for irrigation. The high salinity hazard samples were found mostly in the limestone aquifer in the northern part of the basin as a result of the dissolution of calcite, dolomite and gypsum, which are presented in the Amran limestone.

4.4.2.2. Sodium (Alkali) Hazard (SAR)

Although sodium contributes directly to the total salinity the main problem with a high sodium concentration is its effect on the physical properties of soil. While a high salt content (high EC) in water leads to formation of saline soil, high sodium content (SAR) leads to development of an alkaline Groundwater Quality Assessment for Different Purposes in Sana'a basin. Irrigation with Na-enriched water results in ion exchange reactions: uptake of Na+ and release of Ca^{2+} and Mg^{2+}. This causes soil aggregates to disperse, reducing its permeability (TIJANI, 1994). The sodium or alkali hazard in the use of water for irrigation is determined by the absolute and relative concentration of cations and is expressed as the sodium adsorption ratio (SAR).The equation 3 is used to calculate SAR (APPELO and POSTMA, 2007):

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad \textbf{(eq. 3)}$$

Ions in the equation are expressed in milliequivalent per liter. There is a significant relationship between SAR values of irrigation water and the extent to which sodium is absorbed by the soils. Continued use of water with a high SAR value leads to a breakdown in the physical structure of the soil caused by excessive amounts of colloidally absorbed sodium. This breakdown results in the dispersion of soil clay that causes the soil to become hard and compact when dry and increasingly impervious to water penetration due to dispersion and swelling when wet. Fine-textured soils, those high in clay, are especially subject to this action.

The calculated value of SAR in the study area ranges from 0.27 to 10.44 meq/l in ground waters and from 0.16 to 0.75 meq/l in the spring water samples (Fig. 6). The SAR values plotted on the US salinity diagram as alkalinity hazard shows that alkali or sodium hazard for water samples (ground- and spring water samples) in the Sana'a basin are classified as low (89%), medium (8%) and high (3%). As per the Richard (1954) classification based on SAR values (tab. 3), most of the samples are excellent category. Thirty-three (out of 37) samples fall in the low sodium hazard category (S1), four groundwater samples belong to the medium sodium hazard category (S2) and one groundwater sample falls in the high sodium hazard category (S1) . The source of sodium is most likely natural and could be result of dissolution of the volcanic rocks.

Table 3: Salinity and Alkali Hazard Classes (Richard ,1954)

Water Quality	sodium adsorption ratio (meq/l)
Excellent	<10
Good	10-18
Doubtful	18-26
Unsuitable	> 26

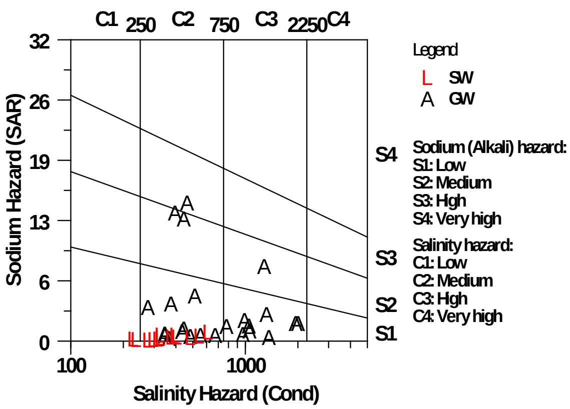

Figure 9: SAR of ground- and spring water samples

4.4.3. Classification based on Magnesium Hazard

Calcium and magnesium ions are essential for plant growth but they may associated with soil aggregation and friability. Water contains calcium and magnesium concentration higher than 10 meq/l (200 mg/l) can not be used in agriculture. In the study area the concentrations of calcium and magnesium were found to be below 200 mg/l, only in two of the groundwater samples GW5 and GW-6 exceed the calcium the values 200 mg/l with 326 and 321 mg/l, respectively (table 1 and 2 in the appendix).

Another indicator can be used to specify the magnesium hazard (MH) is proposed by SZABOLCS and DARAB (1964) for irrigation water as in the equation 4:

$$MagnesiumHazard(MH) = \frac{Mg}{Mg + Ca} * 100 \quad \textbf{(eq.4)}$$

If this percentage hazard was less than 50, then the water was safe and suitable for irrigation.

From the calculated value, the magnesium hazard values range between 4.2-37.3% (tab. 3 and 4 in the appendix), and can be classified as suitable for irrigation use.

4.4.4. Classification based on saturation index (SI)

The SI gives information about how much a certain mineral phase (e.g. calcite, Gypsum) has dissolved in the solution relative to the amount it can potentially solve. If the calculated SI= 0, there is equilibrium between the mineral and the solution, while the negative values (SI< 0) indicates an undersaturation and positive values (SI>0) oversaturation (APPELO and POSTMA, 2007).

The saturation indices for a total of 37 spring and groundwater samples collected from Sana'a basin were calculated and modeled with the software Aquachem 4.0 for calcite, dolomite, anhydrite and gypsum. The calculated values are presented in the table 3 and 4 in the appendix and shown in Figure 7.

According to the calculated SI values, the groundwater samples are classified in three categories; most of the samples are classified to be unsaturated in calcite, dolomite, anhydrite and gypsum; tow samples collected from limestone aquifer (GW-5 and GW-6) are oversaturated in calcite and dolomite with SI-values 0.6 and 0.8, respectively, but undersaturated in anhydrite and gypsum; tow others samples (GW-3 and GW-11) are in equilibrium with calcite, but undersaturated with respect to the other three minerals.
All the spring water samples are classified to be undersaturated (SI<0) with the minerals calcite, dolomite, anhydrite and gypsum.

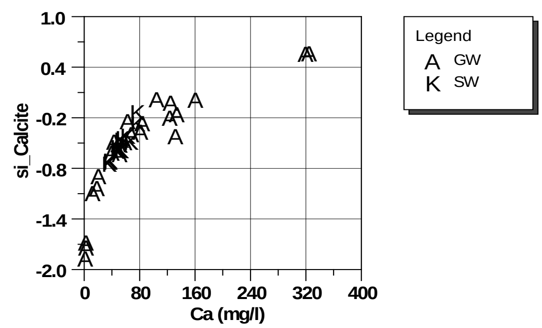

Figure 10: SI of springs and groundwater samples in respect to calcite

4.4.5. Classification based on Piper diagram

The chemical analyses data were plotted in PIPER diagram with the software AQUACHEM 4.0 to visualize the general chemical characteristics and to classify the ground- and spring water samples in groups of similar geochemical properties.

The Piper diagram in AquaChem plots the major ions as percentages of milli-equivalents in two base triangles. The total cations and the total anions are set equal to 100% and the data points in the two triangles are projected onto an adjacent grid. This plot reveals useful properties and relationships for large sample groups. The main purpose of the Piper diagram is to show clustering of data points to indicate samples that have similar compositions.
In the Piper diagram four major groups of ground- and spring water and a single group can be distinguished. Most samples were classified as earth alkaline waters with prevailing hydrogenbicarbonate (group 1) or sulphate as in group 2.

Group 1: water type Ca-HCO3 (low mineralized)

his type of water represents the major water type in the study area and dominates the western part of the Sana'a basin. 12 out of 13 spring water samples and 6 of the groundwater samples. Generally, this water type is characterized by predominant hydrogencarbonate and low electrical conductivities ranging from 230 to 560 µS/cm. The low mineralization and the low content in alkalis and earth alkalis are due to the low temperatures of spring and groundwater, affecting the solubility. In sample GW-14 in the sandstone aquifer an increase in chloride concentration was observed, indicating that this sample is influenced by the infiltration of sewage water. A high concentration in NO_3 was found in this sample. An increase in Mg concentration in samples (GW-10) and (SW-2) in the limestone aquifer is thought to result from the dissolution of limestone from the Amran group.

Group 2: water of Ca-Na-Mg-HCO_3 (SO_4 -CL)

This type of water includes samples GW-3, GW-5, GW- 6, GW-9 in the limestone aquifer, GW-1, GW4, GW-7 in the sandstone aquifer and GW-2 and GW-16 in the alluvium aquifer, about a quarter of the total samples. The water is characterized by medium to high electrical conductivities ranging from 680 to 2030 µS/cm, an increase of sulphate concentrations compared to group 1 and elevated chloride concentrations accompanied by high concentrations of NO_3 which refers to the infiltration of sewage water around Sana'a city. High concentrations of SO_4, Mg and HCO_3 in this group are thought to result from the dissolution of calcite, dolomite and gypsum, or combination of these minerals, which are all present in the Amran limestone (SAWAS, 1996). This water type occurs commonly in the north-east part of the basin and in the central of Sana'a city.

Group 3: water of Ca-Na-HCO3 (CL)

This group is represented by three samples, GW-11, GW21 and SW-7. The samples GW-21 and SW-7 plot are of similar background composition. Electrical conductivity is moderate in GW-21 and SW-7 with 450 and 620 µS/cm, respectively. The limestone sample GW-11 is characterized by a higher EC value with 1340 µS/cm and an increase in the concentration of SO_4 (125 mg/l), Na (142 mg/l), HCO_3 (466.2 mg/l) and Mg (44 mg/l).

Group 4: water of Na-HCO3 (SO4 -CL)

Six samples belong to this water type which is characterized by high Na and low Ca and Mg. This water occurs mainly in the volcanic aquifer in the southern part of the basin (samples GW-18, GW-19, GW-20 and GW-22); however, also sample (GW-8) in the limestone aquifer and (GW-12) in the alluvium aquifer north of Sana'a City belong to this group. Waters with high Na+ and low Ca2+ and Mg2+ are often derived either from thermal sources or from groundwaters that are localized in the acidic volcanics. The volcanic and alluvium groundwater samples are characterized by moderate EC ranging between 380 to 520 µS/cm and moderate concentration in SO_4 and HCO_3 (between 41 to 70 and 144.9 to 207.9 mg/l respectively). The limestone sample shows increased EC (1300 µS/cm) as well as an increase in SO_4, Ca, HCO_3 and Mg concentrations with 330, 44.6, 378 and 26.5 mg/l, respectively. Chloride was found in all samples of this group in moderate concentrations ranging between 42 to 75 mg/l.

Group 5 (single sample): water of Na-K-HCO3

The sample GW-23 comes from the volcanic aquifer in the south-west part of the basin. It was collected from a deep well with total depth of 450 m; the depth to the water table is 255 m. According to the owner, the well was recently deepened. The water is used for irrigation purposes. This sample can be classified as alkaline water which is dominated by Na, K and HCO_3. The high concentration of alkaline minerals is natural and results from the dissolution of these minerals in the volcanic host rocks.

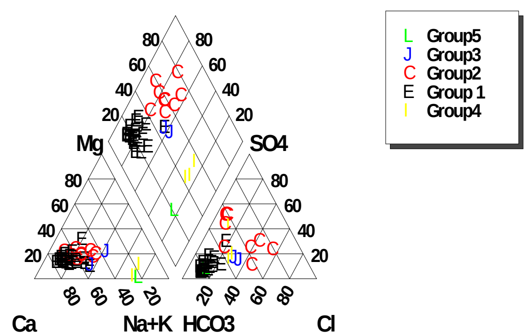

Figure 11: Piper plots of the ground- and spring water samples

5. Water quality in sana'a basin

To ascertain the suitability of ground- and spring water of the Sana'a basin for drinking as well as irrigation purpose, physicochemical parameters of the water samples taken from the Sana'a basin are compared with the guideline recommended by WHO and NWRA drinking water standard. The standards of NWRA generally apply to two limits, the Optimal Limit (OL) and Maximum Permissible Limit (MPL). Because there are no guidelines for Bromate (Br) recommended by NWRA and WHO, the concentration was compared with Europe Unions standards (EU-standard). The result of the comparison is presented in table 1 and 2 in the appendix.

Generally, it can be said that the ground- and spring water in the Sana'a basin is considered to be good for drinking purposes. Some of ground- and spring water samples exceeded the concentrations of HCO_3, SO_4 and NO_3 in the WHO-standard, but do not exceeded the standard values recommended by NWRA in 2000.

The calculated values of the total hardness (Ca^{+2} and Mg^{+2} hardness) exceeded the WHO and NWRA recommendations in four out of 24 groundwater samples,

three of them collected from the limestone aquifer and one from sandstone aquifer (tab. 4 and 5 in the appendix).

A classification of water based on SAR was carried out to ascertain the suitability of water for irrigation purposes. The calculated TDS and SAR indicate that the water of the Sana'a basin is suitable for irrigation purposes. The water was classified based on SAR as excellent.

Although the water quality in the Sana'a basin is still good, but it is contaminated mostly by the infiltration of sewage water and salinization due to high ground water abstraction (high EC values were found).

The nitrate and chloride reach the groundwater in deep wells in the different aquifer systems. The highest concentration of NO3 and Cl at the maximum total well depth 450 m was found to be 33 and 190 mg/l, respectively. The source of the both anions in the groundwater is the infiltration of the wastewater through the cesspits (SAWAS, 1996 and Al-HAMDI, 2000).

CONCLUSION

Elevated chloride concentrations accompanied by high concentrations of nitrate in groundwater can be observed in the central and northern part of Sana'a, particularly in the alluvium and sandstone aquifer, resulting from the infiltration of wastewater.

High EC values are found in the samples collected from the limestone aquifer in the north-eastern part of the basin due to dissolution of calcite, dolomite and gypsum in the Amran limestone.

The groundwater quality in the Sana'a basin is considered to be suitable for irrigation and drinking purposes.

REFERENCES

[1] Al-HAMDI, M.I. (2000): Competition for Scarce Groundwater in the Sana'a Plain, Yemen. Delf University-Netherlands, PhD thesis, 2000.

[2] APPELLO, C.A.J., POSTMA, D. (2007): Geochemistry, Groundwater and Pollution, 2nd, Netherlands, p.649.

[3] AQUACHEM V.5.1 USER'S MANUAL (2007): Water Quality Data Analysis, Plotting, and Modeling, 2007.

[4] DAVIS, S.,N. (1966): Hydrogeology. John Wiley & Sons, New York, p463.

[5] FOPPEN (2002): Impact of high-strenght wastewater Infiltration on groundwater quality and drinking water supply: the Case of Sana'a, Yemen, Journal of Hydrology 263 (2002) 198- 216.

[6] HEM J. D. (1985): Study and interpretation of the chemical characteristics of natural water, USGS Water Supply Paper, 1985, 2254, 117-120.

[7] NWRA (2000): Water Quality Standard. Report No. 2000/100, unpublished report.

[8] RICHARDS (1954): Diagnosis and improvement of saline alkali soils, vol. 160. Handbook 60, US department of agriculture, Washington DC.

[9] SAWAS (1996): Sources for Sana'a Water Supply. Final technical report and executive summary. Netherlands Institute of Applied Geosciences TNO, Delft, the Netherlands.

[10] SZABOLCS I, DARAB C. (1964): The influence of irrigation water of high sodium carbonate content of soils. In: Proceedings of 8th International Congress of Isss, Trans, vol II, pp 803–812.

[11] TIJANI (1994): Hydrochemical assessment of groundwater in Moro area, Kwara State, Nigeria, Environ. Geol. 24:194–202.

[12] TODD D.K. (1980): Groundwater hydrology, 2nd ed. John Wiley&sons, Newyork.

[13] WEC (2002): Basin characterisation and selection of pilot study areas. Vol. II Water resource availability and use. Sana'a Basin Water Resources Management Study (SBWRM - PPT). Final Report.

[14]WEC (2006): Evaluation of monitoring activities in Sana'a Basin, Technical Report (2003-2005), June 2006, unpublished report.

[15]WEIGHT, W.,D. (2008): Hydrogeology Field Manual, 2nd Edition, McGraw-Hill, USA, 2008,p751.

[16]WHO (2004): Guidelines for drinking water quality recommendations, vol. 1 Recommendations. 3rd ed. World Health Organization, Geneva, Switzerland, 2004, p. 515.

[17]Yang XH, She DX, Yang ZF, Tang QH, Li JQ.: Chaotic Baye sian Method Based on multiple criteria decision making (MCD M) for Forecasting Nonlinear Hydrological Time Series, Intern ational Journal of Nonlinear Sciences and Numerical Simulatio n, 10(11-12),1595-1610, 2009.

Table 1: Physicochemical characteristics of groundwater samples collected from Sana'a basin

Sample ID	Well description				Physico-chemical			Cations (mg/l)				Anions (mg/l)					TDS (mg/l)	Ion Error %
	Aquifer type	depth of well	depth to WT	Elevation (m)	pH	T (C°)	EC µs/cm	Mg	Na	K	Ca	CL	Br	NO3	SO4	HCO3		
GW-1	S.S	300	140	2233	7,0	26	790	20.3	64.5	4.9	82.6	129	0.4	0.5	125	214.2	513.5	4.91
GW-2 (dug)	Alu.	70	60	2244	8,0	23	1070	23.8	56.5	2.7	133	197	2	73	124	126	695.5	-0.63
GW-3	L.S	160	55.14	2181	7,5	27	1380	35.2	25.7	5.4	162	32	0.5	0.3	326	315	897	-1.25
GW-4	S.S	150	120	2093	7,1	28	1002	40.4	119	3.3	135	225	2.5	23	237	252	651.3	-0.79
GW-5	L.S	250	210	2009	6,3	36	1970	72	152	16.4	326	64	0.6	0.2	812	787.5	1280.5	-1.98
GW-6	L.S	250	220	2006	6,3	35	2030	74.5	149	15.5	321	62	0.8	5	780	781.2	1319.5	-1.55
GW-7	S.S	150	80	2130	5,6	32	680	23.9	27.6	5.1	85.2	47	0.7	42	98	258.3	442	-2.33
GW-8	L.S	56	39	2102	7,6	25	1300	26.5	274	3.6	44.6	75	1	34	330	378	845	1.05
GW-9	L.S	250	210	2130	7,0	32	1060	39.6	86.8	7.1	126	42	0.6	5	292	371.7	689	0.11
GW-10	L.S	350	342	2291	7,2	33	560	27.1	27.1	4.8	64	19	0.3	3	37	333.9	364	-0.39
GW-11	L.S	450	320	2152	7,2	28	1340	44	142	9.2	106	190	0.7	33	125	466.2	871	-1.31
GW-12	Alu.	160	32.92	2176	8,2	28	520	3.8	94	2.3	22	69	0.6	13	70	207.9	338	-5.84
GW-13	S.S	280	180	2546	7,6	27	350	8.6	23	3.7	41.3	18	0.3	21	17	195.3	227.5	-3.27
GW-14	S.S	200	170	2557	7,2	21	490	9.6	20.3	9.6	69.4	43	0.3	38	33	207.9	318.5	-2.40
GW-15	S.S	160	130	289	7,4	23	370	8.1	11.1	10.8	51	20	0.3	27	14	201.6	240.5	-3.67
GW-16 (dug)	Alu.	60	40	2264	8,1	24	980	24.6	38.8	2	125	133	1.2	121	52	214.2	637	-0.77
GW-17 (dug)	Alu.	80	60	2294	8,1	23	440	8.1	33.5	1.8	52.8	27	0.4	21	25	195.3	286	-0.11
GW-18	V	400	320	2338	9,4	31	400	0.2	89.4	1.1	2.9	45	0.6	0.8	46	151.1	260	-3.67
GW-19	V	150	120	2428	8,9	29	470	0.25	111.3	0.8	3.9	42	0.4	0	42	176.4	305.5	0.61
GW-20	V	450	255	2379	9,0	32	450	0.18	99.5	0.4	4.1	46	0.7	0.3	47	144.9	292.5	-0.58
GW-21	V	300	250	2384	7,7	27	450	7.9	40.6	1.4	52.5	31	0.5	6.5	76	157.5	292.5	-0.38
GW-22	V	450	250	2322	8,3	22	380	2.1	70.5	0.9	19.9	45	0.6	3	41	151.2	247	-2.25
GW-23	V	450	255	2558	8,2	26	280	1.8	54	1.1	13.5	18	0.3	1.5	18	182.7	182	-4.97
GW-24	V	120	84	2927	7,5	20	350	7.3	19.5	1.7	59.5	21	0.3	21	17	182.7	227.5	1.02
WHO-Standard					6.5-8.5		1500	150	200	200	200	250	0.01 (E)	50	250	240	1000	
NWRA-Standard *					6.5-9	25	2500	150	400	12	200	600	No GL.	50	400	500	1500	

Table 2: Physicochemical characteristics of spring water collected from Sana'a basin

Sample ID	Lithology	Location			Physico-chemical			Cations (mg/l)				Anions (mg/l)					TDS (mg/l)	Ion Error %
		N	E	Elevation (m.a.s.l)	EC µs/cm	pH	T (C°)	Mg	Na	K	Ca	CL	Br	NO3	SO4	HCO3		
SW-1	V	1689925	411332	2455	330	8.2	23	7.3	21.5	1	48.9	14	0.3	15	12	189	214.5	0.17
SW-2	L.S	1739706	444175	2103	550	7.2	21	18.2	24.8	2.8	77.5	27	0.4	11	44	359.1	357.5	0.09
SW-3	S.S	1710238	381567	2502	300	6	22	5	6.5	0.9	36.5	12	0.2	5	10	151.2	195	-4.31
SW-4	A contact with S.S	1710146	381505	2460	230	8.2	19	5.1	8.2	0.8	37.9	13	0.2	2	11	157.5	149.5	-5
SW-5	A contact with S.S	1711566	379465	2500	240	7.1	21	6.4	6.4	1.5	37.6	11	0.2	9	11	157.5	156	-4.44
SW-6	S.S	1710881	385063	2541	280	8.4	21	6.6	6.4	2.6	50.1	11	0.2	3	26	170.1	182	-4.58
SW-7	S.S	1715056	382618	2582	620	7.4	22	10.5	35.6	32.9	67.8	61	0.4	69	53	182.7	403	-2.14
SW-8	S.S	1717753	376514	2752	320	6.7	22	7.8	8.5	2.9	48.5	15	0.2	13	40	176.4	208	-1.10
SW-9	Vcontact with A	1714999	385890	2522	490	7.7	23	15	16.9	1	77.6	34	0.4	10	56	258.3	318.5	-5
SW-10	V	1713590	387923	2537	380	9.4	20	10.8	16.5	1	54.5	21	0.5	16	19	214.2	247	-2.65
SW-11	V	1701576	444017	2669	400	7.6	22	9.4	23.2	1.1	56.3	27	0.4	10	37	220.5	260	-2.26
SW-12	V	1691763	392027	2988	410	7.3	18	8.6	17.2	1.4	63.2	18	0.3	22	17	207.9	266.5	-3.48
SW-13	V	1691588	392109	3022	330	8.4	18	7.4	13.1	1	54.2	19	0.3	25	18	157.5	214.5	0.10
WHO -Standard					1500	6.5-8.5	-	150	200	200	200	250	0.01 (E)	50	250	240	1000	
NWRA-Standard					2500	6.5-9	25	150	400	12	200	600	No GL	50	400	500	1500	

- (E): EU-Standard

Table 3: Calculated Ca^{+2} and Mg^{+2} hardness, SAR and SI in the groundwater samples collected from Sana'a basin

Sample ID	Aquifer type	SAR (meq/l)	Total hardness (mg/l)	MH(%)	SI-Calcit	SI-Dolomite	SI-Anhydrite	SI-Gypsum
GW-1	S.S	1.17	289.73	19.7	-0.35	-1.03	-1.74	-1.5
GW-2	Alu.	0.84	430.08	15.2	-0.41	-1.29	-1.61	-1.4
GW-3	L.S	0.34	549.32	17.8	0.03	-0.33	-1.16	-0.9
GW-4	S.S	1.63	503.14	23.0	-0.15	-0.54	-1.38	-1.2
GW-5	L.S	1.40	1110.20	18.1	0.57	0.77	-0.7	-0.5
GW-6	L.S	1.38	1107.95	18.8	0.57	0.78	-0.72	-0.5
GW-7	S.S	0.48	310.99	21.9	-0.25	-0.8	-1.83	-1.6
GW-8	L.S	5.68	220.15	37.3	-0.48	-0.91	-1.7	-1.46
GW-9	L.S	1.22	477.36	23.9	-0.01	-0.25	-1.31	-1.07
GW-10	L.S	0.51	271.11	29.7	-0.23	-0.55	-2.3	-2.09
GW-11	L.S	2.07	445.40	29.3	0.03	-0.04	-1.7	-1.51
GW-12	Alu.	3.44	70.58	14.7	-0.89	-2.36	-2.43	-2.2
GW-13	S.S	0.60	138.51	17.2	-0.60	-1.64	-2.8	-2.51
GW-14	S.S	0.43	212.86	12.2	-0.39	-1.38	-2.31	-2.07
GW-15	S.S	0.27	160.71	13.7	-0.50	-1.53	-2.8	-2.52
GW-16	Alu.	0.59	413.36	16.4	-0.19	-0.81	-2	-1.8
GW-17	Alu.	0.80	165.21	13.3	-0.52	-1.56	-2.51	-2.3
GW-18	V	9.69	8.07	6.5	-2.02	-	-3.57	-3.3
GW-19	V	10.44	10.78	6.0	-1.78	-	-3.45	-3.2
GW-20	V	9.24	10.99	4.2	-1.74	-	-3.23	-3.03
GW-21	V	0.98	163.64	13.1	-0.63	-1.82	-2.04	-1.8
GW-22	V	2.84	58.36	9.5	-1.05	-2.79	-2.67	-2.43
GW-23	V	2.59	41.13	11.8	-1.1	-3.04	-3.14	-2.9
GW-24	V	0.45	178.68	10.9	-0.5	-1.61	-2.62	-2.3
WHO-Standard			500					
NWRA-standard*			500					

Table 4: Calculated Ca^{+2} and Mg^{+2} hardness, SAR and SI in the spring water samples collected from Sana'a basin

Sample ID	lithology	SAR (meq/l)	Total hardness (mg/l)	MH (%)	SI-Calcite	SI-Dolomite	SI-Anhydrite	SI-Gypsum
SW-1	V	0.54	152	13.0	-0.55	-1.64	-2.83	-2.59
SW-2	L.S	0.47	268	19.0	-0.13	-0.6	-2.18	-1.94
SW-3	S.S	0.19	112	12.0	-0.74	-2.05	-2.98	-2.74
SW-4	A contact with S.S	0.23	116	11.9	-0.71	-2	-2.93	-2.7
SW-5	A contact with S.S	0.18	120	14.5	-0.72	-1.99	-2.94	-2.7
SW-6	S.S	0.16	152	11.6	-0.57	-1.78	-2.47	-2.23
SW-7	S.S	0.75	213	13.4	-0.48	-1.5	-2.15	-1.91
SW-8	S.S	0.21	153	13.9	-0.59	-1.73	-2.32	-2.08
SW-9	Vcontact with A	0.33	256	16.2	-0.26	-0.94	-2.05	-1.82
SW-10	V	0.38	181	16.5	-0.46	-1.36	-2.61	-2.37
SW-11	V	0.53	179	14.3	-0.44	-1.39	-2.32	-2.08
SW-12	V	0.38	193	12.0	-0.41	-1.42	-2.6	-2.36
SW-13	V	0.31	166	12.0	-0.58	-1.76	-2.616	-2.38